

Experimental Study of Mystery of Double Slit --- Comprehensive Double Slit Experiments

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Abstract Young's double slit experiments, which represent the mystery of quantum mechanics, have been interpreted by quantum probability waves and pilot waves. In this article, to study the mystery, we introduce the "virtual box" which represents the slide of double-slit and its right-hand neighborhood. Within, and only within, the "virtual box" the standard wave interference patterns are formed. We propose and carry out "comprehensive double slit experiments" that show that, first, light travelling from a laser source towards the slides of double slit and/or cross-double slit behaves as particle (postulate-1), and second, after leaving the "virtual box" zone and being directed towards the detector, the light behaves as a stream of photons (postulate-2) with no further interference due to the slits. On the one hand, the interference patterns do exist in the comprehensive-double slit experiments. On the other hand, we show four novel phenomena: (1) the fringes of the interference patterns are formed independently; (2) the fringes of the interference patterns can be formed partially; (3) the longitudinal shields do not disturb the interference patterns; and (4) the range of the virtual box is less than one inch. These novel phenomena indicate that photons behave as particles, and would not be expected if photons behave as waves created by the double slit and/or cross double slit. The comprehensive-double slit experiments show the coexistence of wave distribution and particle nature of photons in the same experiment, which violates complementarity principle and thus, seems a paradox. We suggest an interpretation to address the paradox. All observations of the comprehensive-double slit experiments are consistent. Progress in studying the mystery of the double slit experiment is presented.

Keywords: double slit experiment, comprehensive double slit experiments, cross-double slit experiment, mystery of double slit experiment, wave function collapse, complementarity principle, wave-particle duality

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1. Introduction

The evolution of the interpretations of the nature of the light/photons went through a long history. In 1801, Young performed a classical double slit experiment [1,2], which demonstrated that light could behave as waves and was consistent with the wave theory of light of Huygens (1678). Then, Descartes (1637)/Newton's (1704) corpuscular-particle theory of light has faded out.

During the years 1886-1902, Heinrich Hertz, Wilhelm Hallwachs and Philipp Lenard investigated the photoelectric effect experimentally [3,4].

The interpretation of nature of light had changed again.

Einstein (1905) proposed that light is quanta [5], which combining with Young's double slit experiment led to wave-particle duality [6]. In 1914, Millikan confirmed Einstein's model experimentally [7].

Louis de Broglie (1924) [8] postulated that quantum particles behave as waves, which was verified for electrons in 1927 (Davisson and Germer) [9]. For double slit experiments, I raise a question: whether the wave nature is the *intrinsic nature* for a particle? The word "intrinsic" means "should be independent on state of

motion", namely "should not depend on whether the particle is uniformly moving or accelerating". Up to date, in double slit experiments, particles move with uniform velocities. It is obvious that accelerating particles have no wave "nature" [10].

Since then, the varieties of the double slit experiments (referred as one dimension (1D)-double slit experiments) have been performed. We divide experiments into two categories: (1) "Group particles level", for example, light beam (Young) and beam of particles; (2) "single particle level", for example, single photon and single particle [11]. More projects focus on single photon double slit experiments and single particle, such as single elementary particle (Roger Bach and co-workers), single atom [12] and single molecule, double slit experiments.

Bohr (1927) proposed the complementarity principle [13] based on theory and experiments [14,15,16]. Bohr implies that it is impossible that objects in quantum mechanics have intrinsic properties that are independent of measuring device. The objects have certain pairs of complementary properties, such as wave and particle, which cannot all be observed or measured simultaneously in the same experiment.

The standard interpretation of Young's double slit experiment is that the light behaves the same as waves

before and after passing through the slide of the double slit. Namely, until strike on a detector/screen, photons behave as waves and interfere [17]. While the interference pattern (referred as 1D-interference patterns) remains, photons are always found to be absorbed at the discrete points of the detection screen, as individual particles; the interference pattern appears via the varying density of these particles hit on the screen [18]. It is interpreted as that the photons behave as waves until land on the detector and are “collapsed” by the detector [19].

To understand the double slit experiments, which-way-double slit experiments have been proposed and performed. Photons are observed near a slit by a photoelectric-device to register the photons. Practically the device blocks the propagation path of photons, namely equivalent to cover a slit [20,21]. When the photons are detected, the interference pattern disappears. The which-way-double slit experiments indicate that photons can behave as either particles or waves, but cannot be detected as both at the same experiment, and thus support the complementarity principle.

The operational definition of “wave/particle” stands for “ability/inability to create interference” [22,23,24]. According to this definition, photons in the which-way experiments show indeed particle nature. Note that this measurement is done near a slit.

Recently, the cross-double slit experiments (referred as 2D-cross-double slit experiments) have been proposed [25] and performed [26], which show complex interference patterns (referred as 2D-interference patterns) (Appendix A1). Thus, the interpretation of double slit experiments should consistently explain the cross double slit experiments as well, which is a criterion.

Furthermore, which-way-2D-cross-double slit experiments have been proposed [27] and performed [28]. Since a cross-double slit consists of two or more double slits crossing to each other, when one observes at one slit of one of double slits, the photons passing through that double slit behave as particles, while photons passing through other double slit(s) still show interference pattern(s) independently (Appendix A2). The observations show the violation of complementarity principle.

To interpret the 2D-cross-double slit experiments and which-way-2D-cross double slit experiments consistently is a challenge.

Feynman called “[the electron double slit experiment] contains the only mystery [of quantum mechanics]” [29]. Namely, if we could understand this double slit experiment, we would gain insight into the heart of quantum theory. The 2D-cross-double slit experiments are more mysterious than Young’s 1D-double slit experiments.

The pilot wave of the de Broglie-Bohm theory provides an alternative interpretation (de Broglie, in “*Ondes et mouvements*” of 1926) [30,31], by which photons propagate along trajectories.

Moreover, the nature of photon puzzled Einstein. He wrote to M. Besso: “All these 50 years of conscious brooding have brought me no nearer to the answer to the question: What are light quanta?” [32].

The history of the evolution of the interpretations of light/photons shows that conceptually novel experiments changed the interpretation of nature of light/photons.

We realized that one of the reasons why the mystery of the double slit experiment is long-standing is the lack of systematic and adequate experimental data. Utilizing only standard 1D-double-slit apparatus is not sufficient for understanding fully the mystery of double slit and the wave-particle duality. Full range double slit experiments with different perspective are needed to study the phenomenon and to provide more basic facts.

In this article, we investigate the double slit experiments at “group particle level” with beam of photons. We start with proposing two postulates and comprehensive-double slit experiments. The latter will test the former. These novel experiments are based on both regular 1D-double slit apparatuses and 2D-cross-double slit apparatuses. One of characteristics of those experiments is that the experimental results are visually observable without ambiguity.

The experimental observations show that photons behave as particles before striking at the slide of double slit and before striking at the detector/screen.

2. A Model and Outline

We first review the standard interpretation of Young’s double slit experiments (Figure 1).

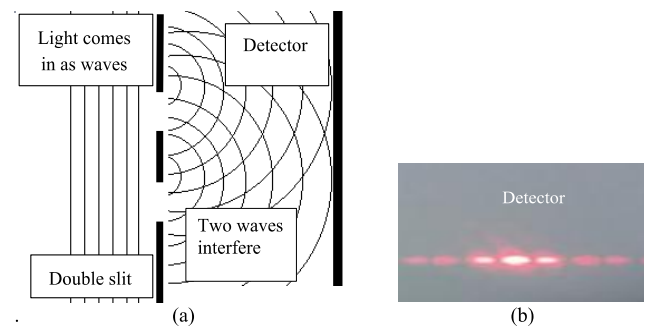


Figure 1. Double slit Experiment

The basic apparatus, consisting of a laser source, a slide of double slit and a detector, is utilized as a complete system. The standard understanding of double slit experiments is considered naturally self-evidence. Thus, when photons assumed to propagate as waves land on a detector actually as particles, the concept of “wave function collapse” is necessary.

To precisely describe the double slit experiments, we introduce a model, in which the slide of a double slit and its right-side neighborhood is represented as a “virtual box” (Figure 2).

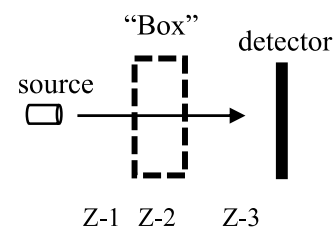


Figure 2. Double slit Apparatus with “virtual box”

Let’s divide the model into 3 zones, zone-1 (Z-1) is from source to the slide t, which is the left boundary of the

Virtual Box; the virtual box is zone-2 (Z-2); zone-3 (Z-3) is from the right boundary of the virtual box to the detector. In this article, we study, how photons behave in zone-1 and zone-3, and estimate the range of the right-boundary of the Virtual Box.

Note that we did not use the terms “near field” and “far field”, because we show below that in Z-3 (or far field) photons behave as particles, but waves. And we will investigate what happening in Z-2 (near field).

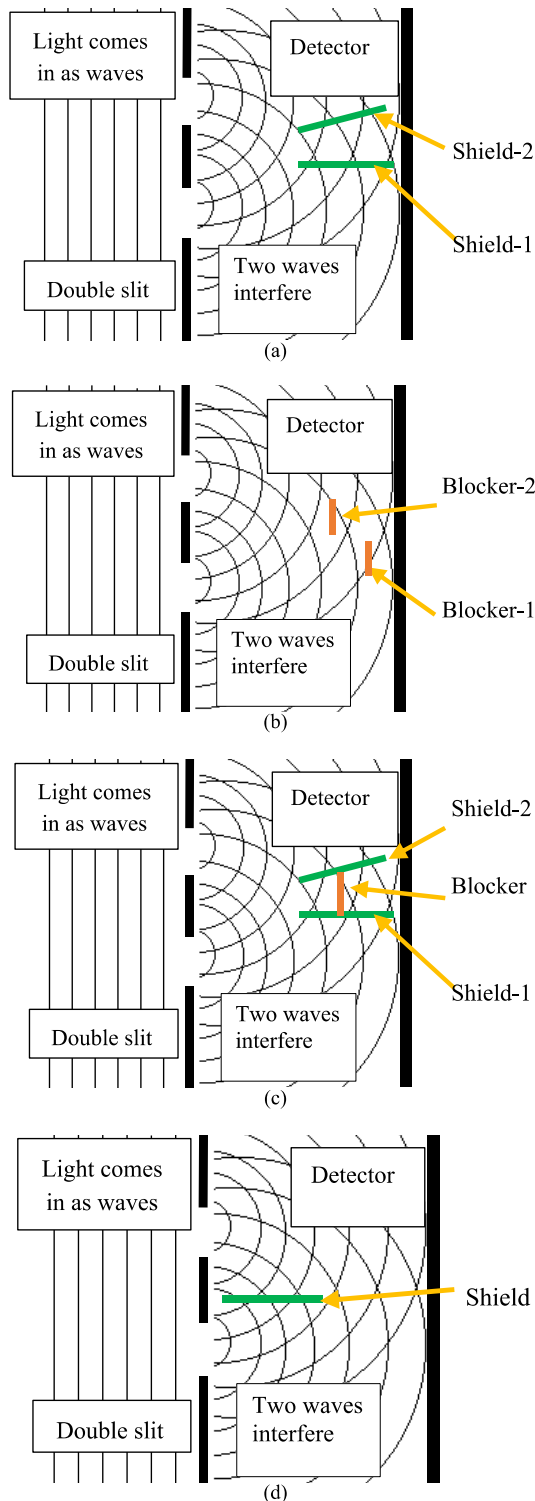


Figure 3. Schematic of Outline

We emphasize that the statement that light behaves as wave before arriving slide and before landing on the

detector, has not been experimentally tested yet. Starting from the wave interpretation, we design experiments to test it. Thus, in the schematic drawings in Figure 3, we adopt the statement that light behaves as waves in the entire experiments.

To test whether photons behave as waves in zone-3, we insert: (1) longitudinal “wave shield(s)” (Figure 3a), denoted as shield; (2) transverse “wave blocker(s)” (Figure 3b), denoted as blocker; (3) combination of shield and blocker (Figure 3c); all near detectors. The purpose is to observe whether the interference pattern would be disturbed by shields and blockers. An analogy is a breakwater that break water waves. To test the right-boundary of the virtual box, a shield is gradually moving towards the double slit (Figure 3d) to determine where photons would start to change behavior if they do change.

However, in the rest of the article, the comprehensive-double slit experiments show that photons actually behave as particles in zone-1 and zone-3. Thus, in the following schematic drawings, there are no wave-shape patterns.

3. Double slit Changing Photons' Behavior

3.1. Two Postulates

We propose two postulates relating to double slit experiments and then test them.

Postulate-1: in zone-1, photons behave as particles.

Postulate-2: in zone-3, photons behave as particles.

Postulate-2 predicts that in zone-3, each fringe is formed independently and can be formed partially. Indeed, the experimental results of testing the prediction strongly support postulate-2.

First, let's experimentally test a rule.

Rule: The particle nature of a single input beam of photons is not changed by a beam splitter (BS), either reflected by the BS or passing through the BS.

Example-1: when a beam of photons outputted from a BS behaves as particles, then the input beam of photons behaves as particles, while the other output beam of photons behaves as particles.

Note that in this article, we do not discuss the situation of two input coherent beams; for example, two beams are inputted into an output beam splitter in a Mach-Zehnder interferometer.

Although the Rule seems trivial, it is necessary to test postulate-1. Let's test the Rule experimentally.

Experiment-1: testing the Rule.

Experimental Setup (Figure 4a): photons reflected by both BS1 and M1 land on detector1 (D1), while photons passing through BS1 land on D2.

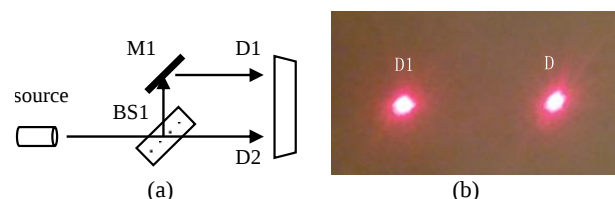


Figure 4. Testing Rule

Observation (Figure 4b): D1 and D2 show the images of the source respectively, which indicate that photons detected on both D1 and D2 respectively have the same particle nature.

The Rule is confirmed by experiment-1.

3.2. Photons Behaving as Particle before Arriving at Double slit

Now let's test postulate-1 experimentally.

Experiment-2: testing postulate-1 in two experimental setups.

Experimental setup-1 (Figure 5a): Photons passing through both BS1 and BS2 strike at D2. Photons reflected by BS1 and M1 and passing through slide-1 strike at D1. Photons reflected by BS2 and M2 and passing through slide-2 strike at D3. All image/patterns are shown on the same detector to visually observe the phenomenon. To show the difference, we use a cross-double slit for slide-1 (Figure 5b) and a standard double slit for slide-2.

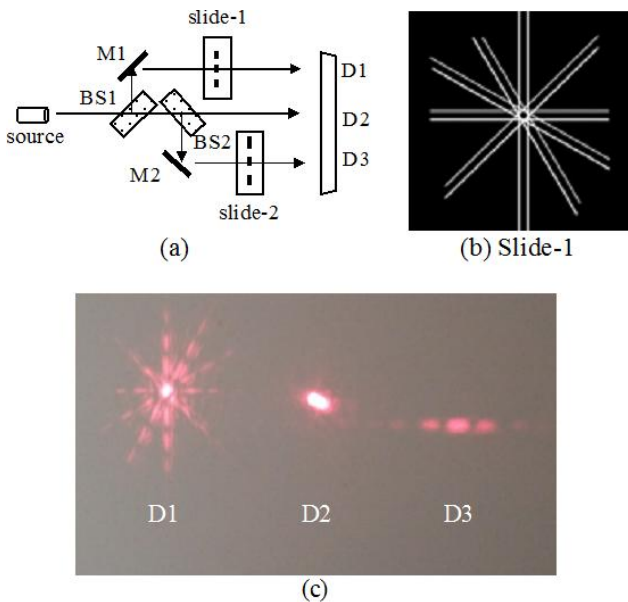


Figure 5. Testing Postulate-1 (1)

Observations (Figure 5c): D2 displays the image of the source, i.e., photons passing through BS1 and BS2 behave as particles. Thus, according to the Rule, photons reflected by BS1/M1 and BS2/M2 traveling towards, respectively, slide-1 and slide-2 behave as particles. Namely, photons behave as particles before arriving double slit/cross-double slit.

On the other hand, D1 and D3 show interference patterns created by the cross-double slit and the double slit, respectively.

We show that before striking at a double slit/cross-double slit, photons emitted by a laser source behave as particles.

Experimental setup-2 (Figure 6a): Photons passing through both BS1 and slide strike at D2. Photons reflected by BS1 and M1 strike at D1. We use a cross-double slit for slide (Figure 6b).

Observation (Figure 6c): D1 shows the image of the laser source, which indicates the particle nature. D2 is an interference pattern created by the cross-double slit.

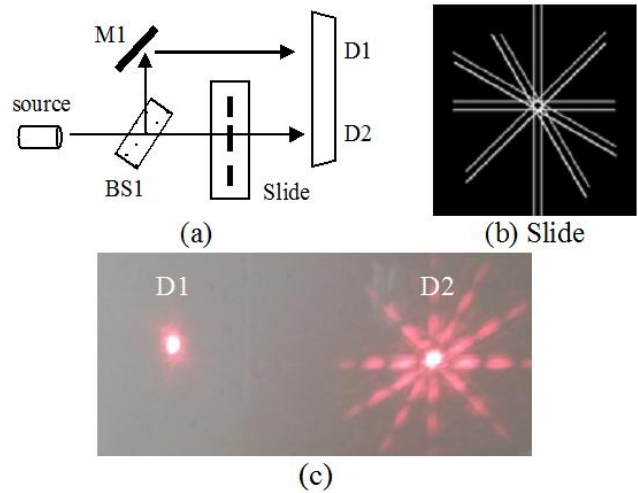


Figure 6. Testing Postulate-1 (2)

Conclusions.

- 1) D1 shows the particle nature of photons. According to the Rule, reflection by BS1 does not affect the nature of photons; thus, photons from the source to D1 behave as particles.
- 2) According to the Rule, passing through BS1 does not affect the nature of photons; thus, the nature of photons passing through BS1 towards the slide is the same as that of photons reflected by BS1, i.e., behave as particles. Before striking on the slide of cross-double slit, photons behave as particles.

Postulate-1 is confirmed experimentally.

Thus, the part of the standard interpretation of double slit experiment, i.e., photons behave as waves before arriving a double slit, is challenged.

3.3. Photons Behaving as Particle before Landing on Detector

Now let's test postulate-2 experimentally.

Note that: (1) since we will show below that photons behave as particles in Z-3, we will not draw wave-shape patterns in the following schematic drawings, not as we did in those drawings in Figure 3; (2) schematic drawings below are not to scale.

3.3.1. Testing Postulate-2 with Longitudinal Shields

Experiment-3: Testing Postulate-2

Experimental Apparatus: Placing a "shield" (green colored) made of carboard in Z-3 of the apparatus of the regular double slit experiments near the detector. The purpose is to test whether the shield would prevent photons from interfering if photons would behave as waves in Z-3. For simplicity, shield-1's orientation is from the center of the double slit points to the center of the zeroth-order-fringe. We refer shield-1 as longitudinal. Shield-1 is 28 inches long, 1.5 inch wide, and 0.3 mm thick. The distance between the double slit and the detector is 200 inches. Shield-1 is assumed to separate waves and thus prevent waves from interfering.

An analogy is a breakwater that break water waves.

Experimental setup-1 (Figure 7a): Shield-1 contacts the detector.

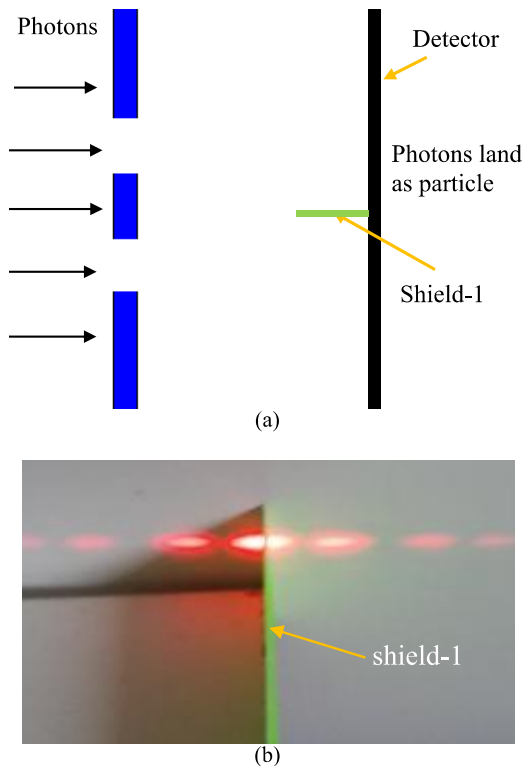


Figure 7. Testing Postulate-2 with Single Shield (1)

Observation (Figure 7b): The interference pattern keeps no change, namely shield-1 does not affect the interference pattern, which would not be expected if photons behave as waves.

Experimental setup-2 (Figure 8a): Shield-1 is one inch away from detector.

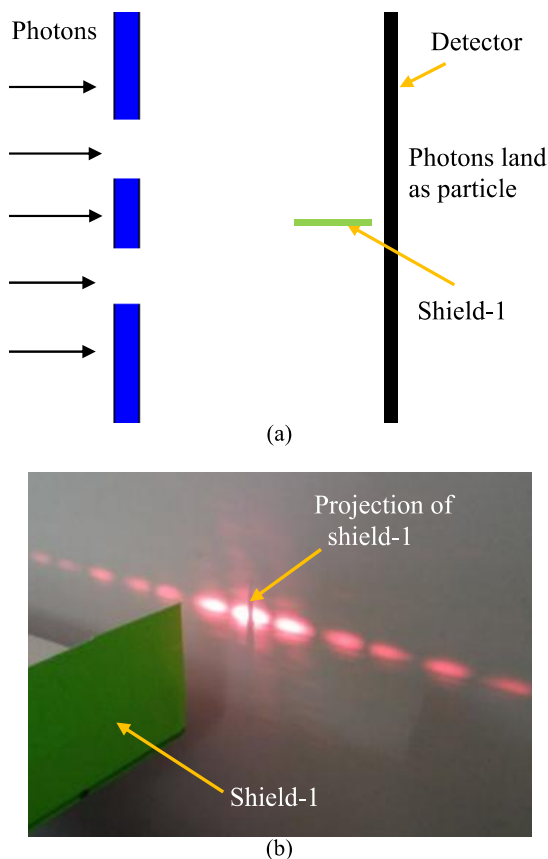


Figure 8. Testing Postulate-2 with Single Shield (2)

Observation (Figure 8b): (1) Shield-1 does not affect the interference pattern; (2) there is the projection of shield-1 at the middle of the zeroth-order fringe.

Phenomena of experiment-3 would be expected only if photons behave as particles.

Experiment-4: Testing Postulate-2

Experimental apparatus: In addition to shield-1, shield-2 is placed into the regular double slit apparatus. Two shields form a narrow channel. The purpose is to test whether the channel would prevent photons from interfering if photons would behave as waves in Z-3. Shield-2 is along the line between the center of the double slit and the center of the first-order fringe and is 28 inches long, 1.5 inch wide, and 0.3 mm thick.

The experiment is carried out in five setups.

Experimental setup-1 (Figure 9a): Both shield-1 and shield-2 contact the detector.

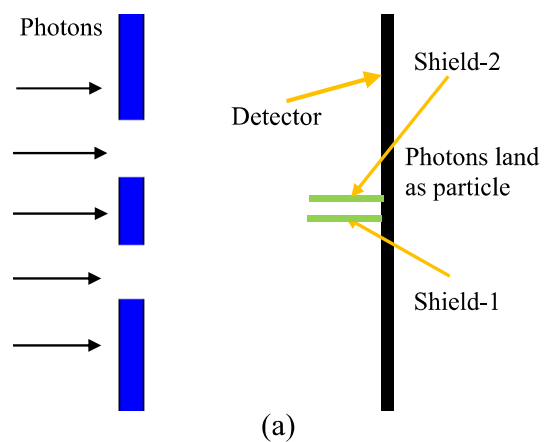


Figure 9. Testing Postulate-2 with Two Shields (1)

Observation (Figure 9b): We observe the interference pattern, which is the same as that there were no shield-1 and shield-2. The existence of two approximately parallel shields of 28 inches long has no effect on the “interference” pattern of 650 nm light, which indicates that photons do not behave as waves. Otherwise, light waves would be prevented from interfering with each other, and the “interference” pattern would be disturbed, especially the zeroth-order and a first-order fringes.

Experimental setup-2 (Figure 10a): Moving both shield-1 and Shield-2 back one inch from the detector.

Observation (Figure 10b): the interference pattern has no change. The projection of shield-1 appears at the middle of the zeroth-order fringe, while the projection of shield-2 appears at the middle of the first-order fringe. Only photons behaving as particles can: (1) pass through the

narrow channel; (2) strike at the positions of the zeroth-order fringe and a first-order fringe on the detector; (3) form two projections, while (4) do not disturb the existing interference pattern.

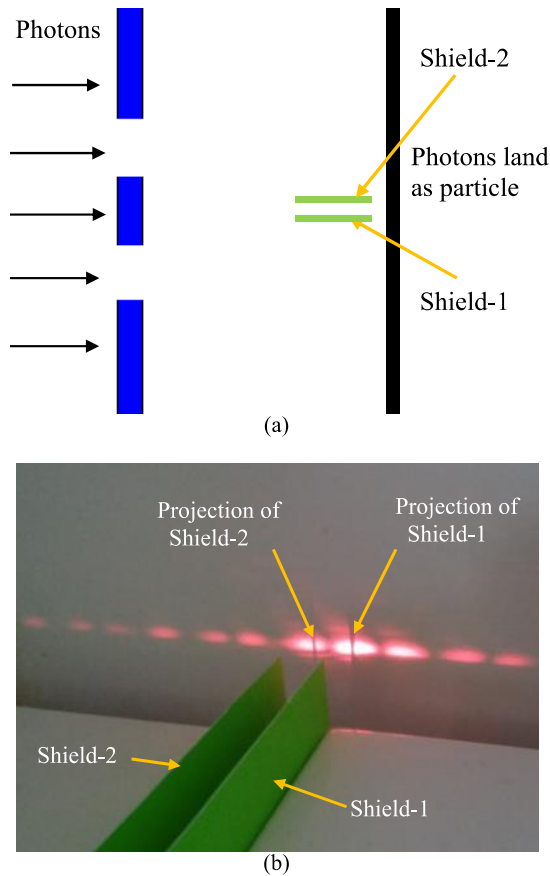


Figure 10. Testing Postulate-2 with Two Shields (2)

Experimental setup-3 (Figure 11a): Picture of whole setup of two shields of 28 inches long contacts to the detector.

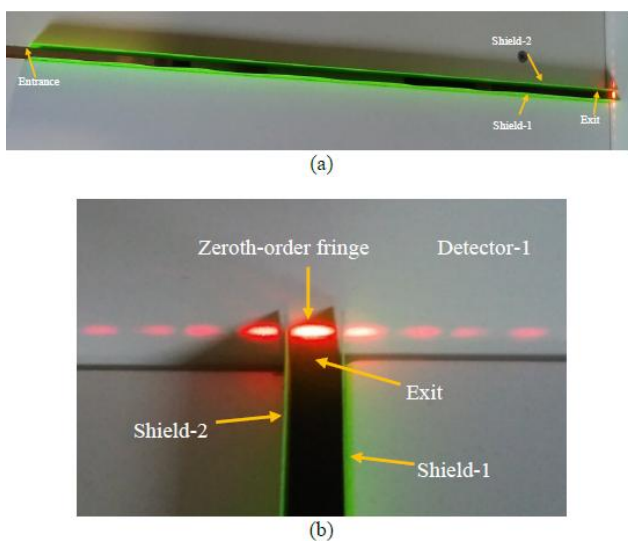


Figure 11. Testing Postulate-2 with Two Shields (3)

Observation: the zeroth-order fringe is shown between shield-1 and shield-2 on the detector, which indicates that the zeroth-order fringe is not the consequence of the interference of two waves, one from the left side of shield-

2, one from the right side of shield-1. The interference pattern is the same as if there were no shield-1 and shield-2.

Experimental setup-4 (Figure 12a): Picture of two shields 70 inches long contact to the detector, which formed a long narrow channel. Note that the picture was shot from the “Entrance” to the detector so that the interference pattern and apparatus show on the same picture and thus, Entrance looks wider.

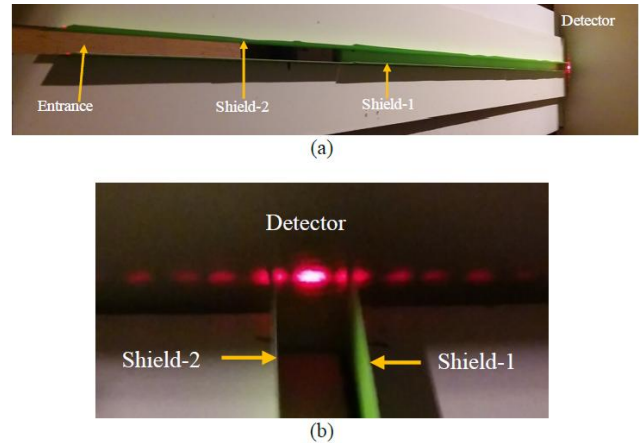


Figure 12. Testing Postulate-2 with Two Shields of 70 inches long (4)

Observation (Figure 12b): the interference pattern is the same as if there were no shield-1 and shield-2. The existence of two long shields has no effect on the interference pattern. Two projections show at the $m = +1$ and $m = -1$ fringes. Observations indicate that photons behave as particles.

Experimental setup-5 (Figure 13a): Shield-2 is placed at 60 inches from double slit; shield-1 stays at the same position as in Figure 10a.

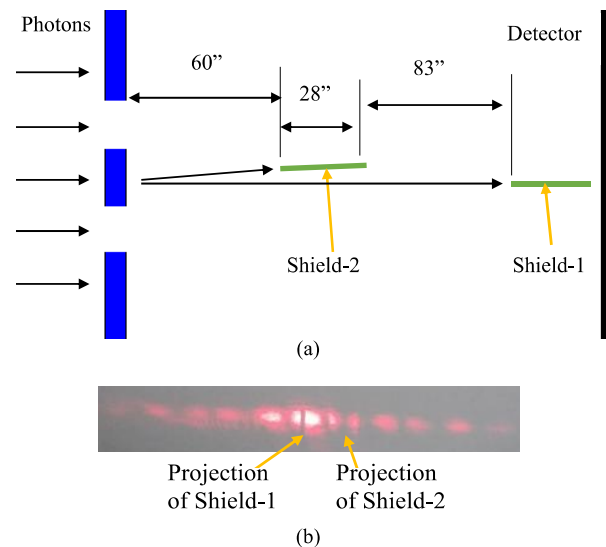


Figure 13. Testing Postulate-2 with Two Shields (5)

Observation (Figure 13b): The interference pattern has no change. The projection of shield-2 is wider than that of shield-1, since it is closer to the double slit.

Comprehensive-double slit experiments have been carried out at different positions, for example, 40 inches, 80 inches, and 120 inches away from the detector. We always observe the interference pattern and projections of shield-1 and shield-2.

Conclusion: Only particles can pass through the long and narrow channel between shield-1 and shield-2, and form fringes on the detector; thus, photons behave as particles long before landing on the detector.

Postulate-2 is experimentally confirmed.

Meanwhile, photons are distributed with a wave-like interference pattern on the detector.

The observations of experiments-3 and -4 violate complementarity principle, in this sense it seems a wave-particle paradox.

I suggest to call the phenomena “wave-particle coexistence”, which would lead to a deeper understanding.

We discuss this paradox/coexistence later and provide an interpretation.

3.3.2. Testing Postulate-2 with Transverse Blockers

Experiment-5: Testing Postulate-2

Let us consider five experimental setups.

Experimental Setup-1 (Figure 14a): blocker-10, blocker-11 and blocker-12, each is 0.5-inch wide, are placed along the normal vector of detector, and separated by 4 inches.

Observation (Figure 14b): Three blockers are arranged such that the zeroth-order fringe and two first-order fringes are formed on blocker-10, blocker-11 and blocker-12 respectively. The existence of each blocker does not affect the fringes formed on other blockers and the detector. Namely, fringes are formed independently.

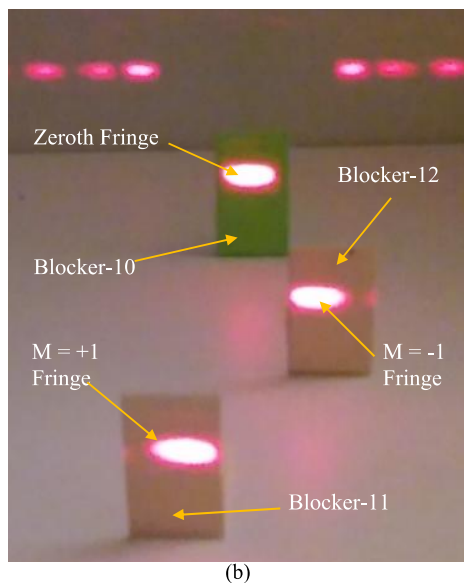
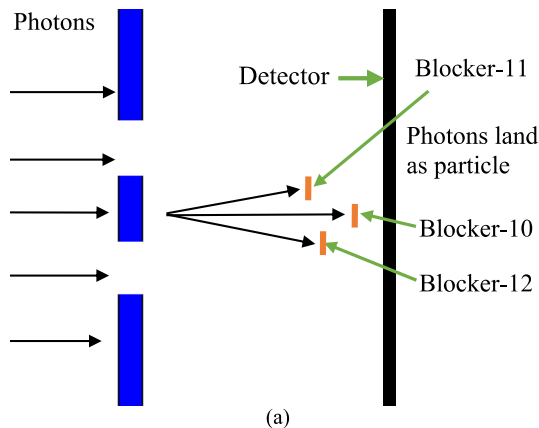


Figure 14. Fringes Formed Independently (1)

Experimental Setup-2 (Figure 15a): blocker-11 and blocker-12 are placed along the normal vector of the surface of the detector, and separated by 4 inches.

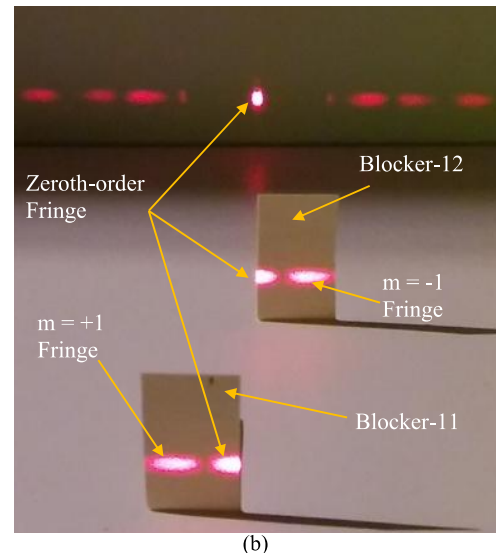
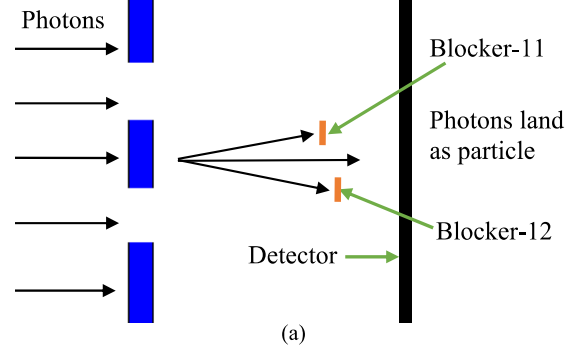


Figure 15. Fringes Formed Independently and Partially (2)

Observation (Figure 15b): Two blockers are arranged such that portions of the zeroth-order fringe are formed on the detector, blocker-11 and blocker-12 respectively. Thus, the fringe can be formed partially. The existence of each blocker does not affect the fringes formed on other blockers and detector. Namely, fringes are formed independently.

Experimental Setup-3 (Figure 16): blocker-11 and blocker-12 are placed along the normal vector of the surface of the detector.

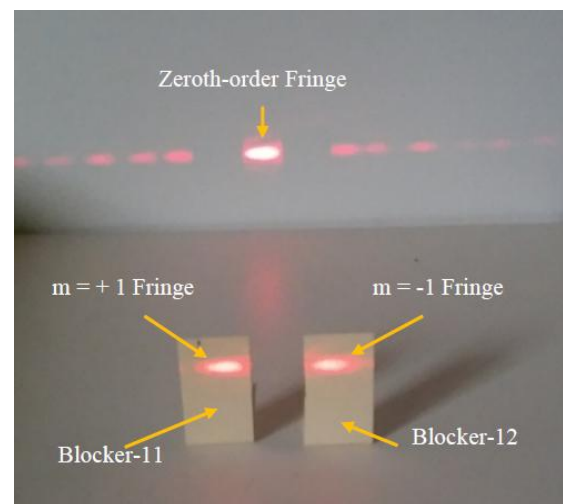


Figure 16. Fringes Formed Independently (3)

Observation: The zeroth-order fringe, $m = +1$ fringe and $m = -1$ fringe are formed on the detector, blocker-11 and blocker-12 respectively.

Experimental Setup-4 (Figure 17): blocker-11 and blocker-12 are placed along the normal vector of the surface of detector, and separated by 4 inches.

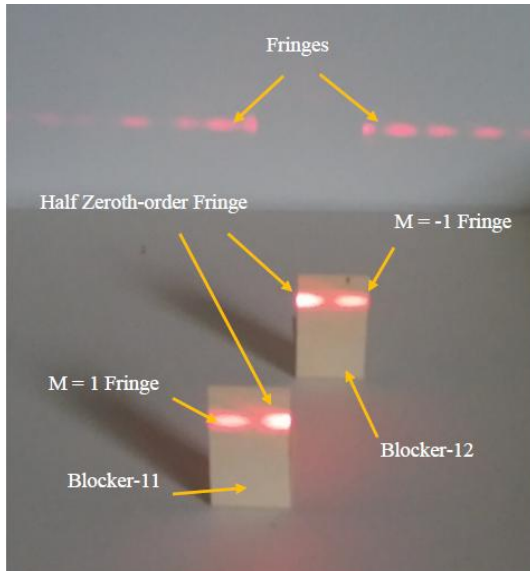


Figure 17. Fringes Formed Independently and partially (4)

Observation (Figure 17): Portions of the zeroth-order fringe are formed on blocker-11 and blocker-12 respectively, which indicates that the fringe can be partially formed. The $m = +1$ fringe and $m = -1$ fringe are formed on blocker-11 and blocker-12 respectively, i.e., formed independently.

Experimental Setup-5 (Figure 18): blocker-11 and blocker-12 are placed along the normal vector of the surface of detector, and separated by 4 inches.

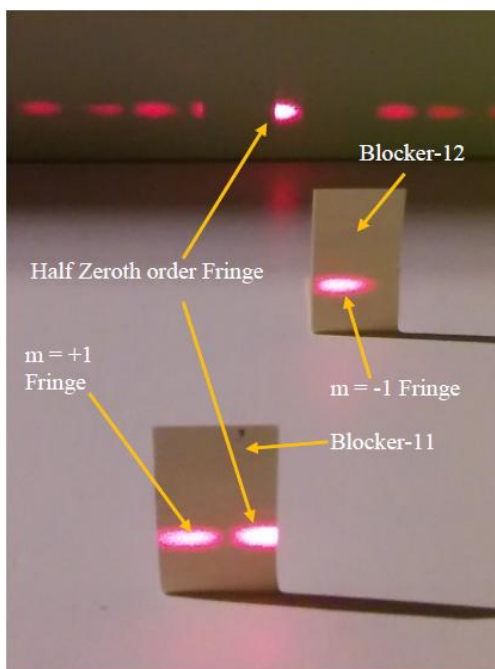


Figure 18. Fringes Formed Independently and partially (5)

Observation (Figure 18): Portions of the zeroth-order fringe are formed on detector and blocker-11 respectively,

which indicates that the fringe can be formed partially. The $m = +1$ fringe and $m = -1$ fringe are formed on blocker-11 and blocker-12, respectively, i.e., formed independently.

Conclusion: Fringes are formed independently and partially, which would be expected only if photons behave as particles in Z-3.

Postulate-2 is experimentally confirmed.

Some of photons form fringes on blockers, meanwhile, some of photons are distributed like partial of a wave interference pattern on the detector.

Experiment-5 shows wave-particle coexistence. We discuss this “coexistence” later.

3.3.3. Testing Postulate-2 with the Combinations of Longitudinal Shields and Transverse Blocker

We have shown that, on the one hand, longitudinal shield(s) do not disturb the interference pattern in zone-3. On the other hand, blockers do block the propagation of photons as photons are particles. Now let's show the effects of combinations of shields and blockers.

Experiment-6: Testing Postulation-2

Experimental setup-1 (Figure 19a): Shield is one inch away from detector. Blocker is positioned next to shield.

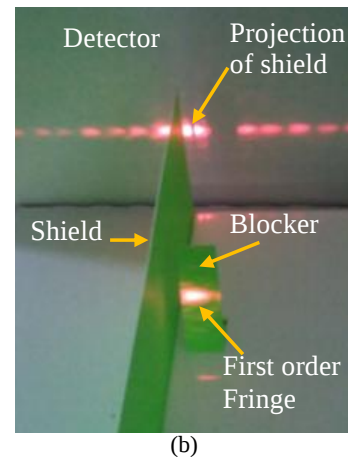
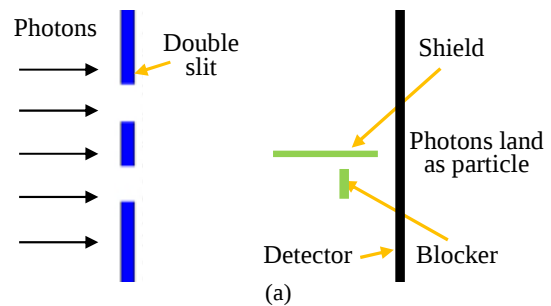


Figure 19. Testing Postulate-2 with Shield and Blocker (1)

Observation (Figure 19b): (1) Shield does not affect the interference pattern at all; (2) there is the projection of the shield at the middle of the zeroth-order fringe; (3) blocker is so arranged that it does block a first-order fringe.

Experimental setup-2 (Figure 20a and 20c): Shield is one inch away from detector. Blocker-1 and blocker-2 are placed on both sides of shield respectively.

Observation (Figure 20b and 20d): Blocker-1 and Blocker-2 are so arranged that the portion of the zeroth-order fringe is formed on blocker-1, rest is formed on blocker-2. Two first-order fringes are formed on blocker-1 and blocker-2, next to the half of the zeroth-order fringe,

respectively. Shield can divide the zeroth-order fringe into two parts, but cannot disturb the rest of fringes, which indeed indicates that photons behave as particle before landing on detector.

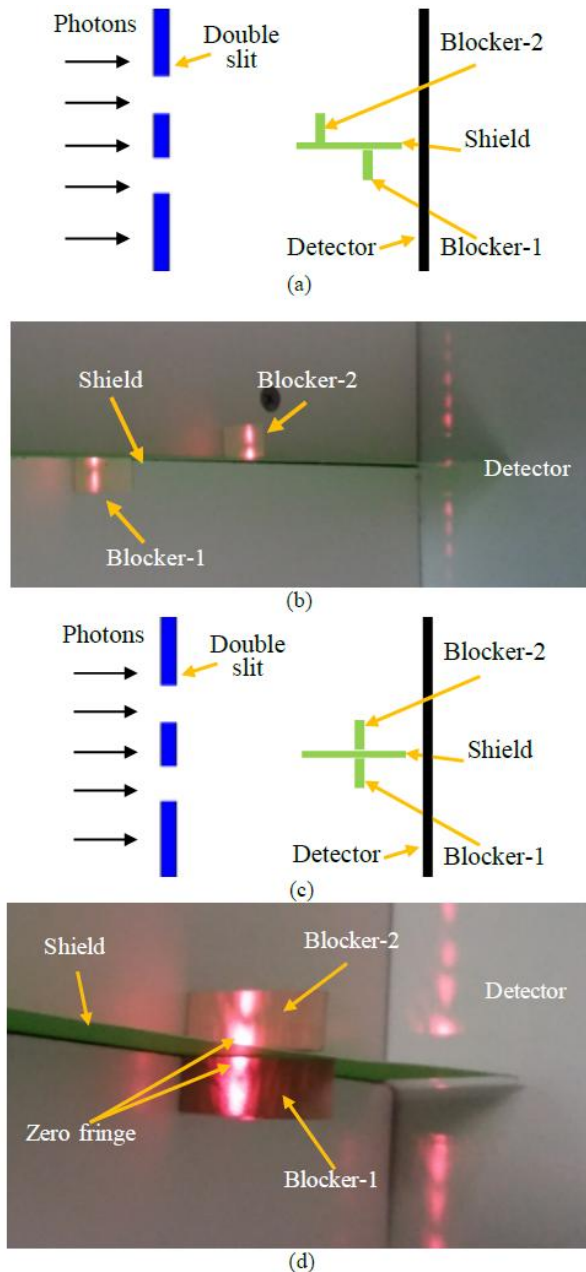


Figure 20. Testing Postulate-2 with Shield and Blockers (2)

Experiment-7: Testing Postulation-2

Experimental setup (Figure 21): Now let us place blocker-1 at the other end of shield-1 and shield-2, where we denote it as Entrance, i.e., photons enter the narrow channel between shield-1 and shield-2 from there (Figure 21b). The interference pattern is formed on blocker-1 instead of the detector (Figure 21b).

We perform this experiment in two setups.

Experimental Setup-1 (Figure 22a): Cutting the top portion of blocker-1.

Observation (Figure 22b): the bottom half of the fringes still show on blocker-1, while the top half show on the detector. Namely all fringes can be formed partially. And shields have no effect on interference pattern at all.

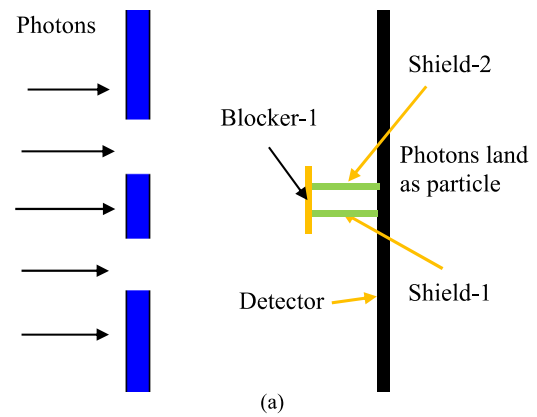


Figure 21. Testing Postulate-2 with Shields and Blocker

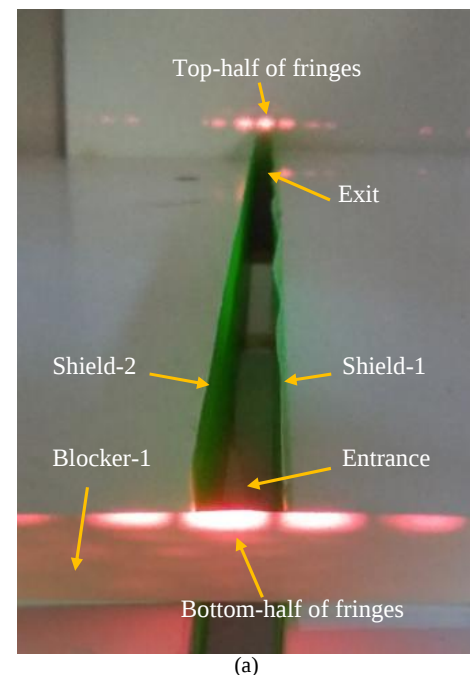


Figure 22. Testing Postulate-2: Cut Top Half of Blocker-1 (1)

Experimental Setup-2 (Figure 23b): cut a “U” shape gap at the position of the zeroth-order fringe on blocker-3.

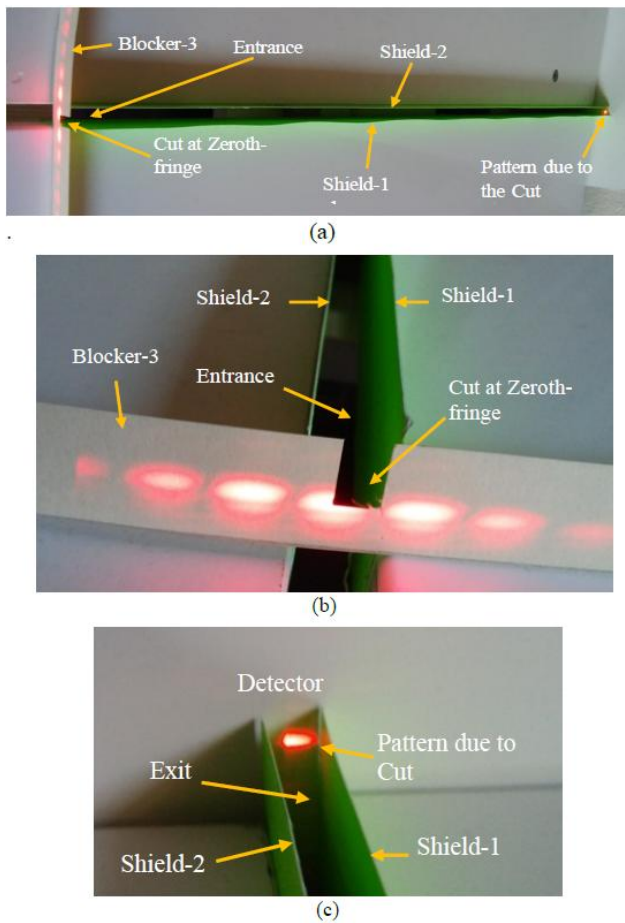


Figure 23. Testing Postulate-2: Blocker-3 with Cut (2)

Observation (Figure 23c): Photons pass through the cut and form the exactly same shape of patterns on the detector, which shows the particle nature of light and indicates that photons move along straight lines.

Experiment-8: Testing Postulate-2.

We perform this experiment in two setups.

Experiment Setup-1 (Figure 24a): insert transverse blocker-2 one inch wide into the channel formed by shield-1 and shield-2.

Observation (Figure 24b): Two fringes are formed on blocker-2, and the remaining fringes are formed on the detector. Namely, Fringes can be formed independently. Two shields have no effect on the interference pattern.

This observation indicates that photons behave as particles. **Experimental Setup-2** (Figure 25): cut triangles on blocker-2 at the locations of the zeroth-order fringe and the first-order fringe. Then place blocker-2 into the channel.

Observation (Figure 25): Photons pass through two triangle-shaped cuts and form exactly the same triangle-shaped patterns on the detector, which shows the particle nature of photons and shows that photons move along straight lines. Note that photons are not directly from the source; they are just pass through a double slit and were supposed to behave as waves. The conclusion is that photons behave as particles.

Postulate-2 is confirmed experimentally.

Meanwhile, some of photons are distributed like a partial wave interference pattern on the detector.

Experiment-6, -7 and -8 challenge the complementarity principle and show “wave-particle coexistence”.

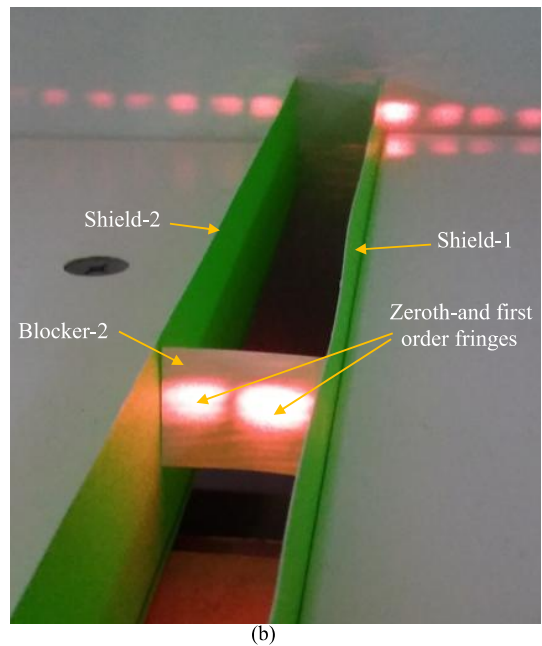
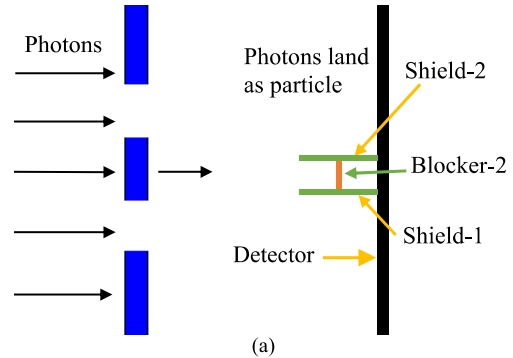


Figure 24. Blocker-2 in Channel (3)

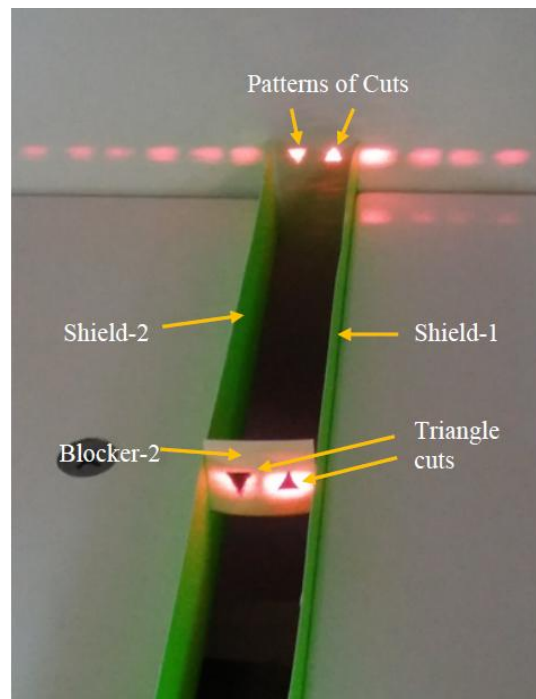


Figure 25. Blocker-2 with Two Cuts (4)

3.3.4. Testing Postulate-2 with 2D-cross-double Slit

The 1D-double slit apparatus/experiments have been extended to 2D-cross-double slit apparatuses/experiments [25,26], which have many varieties (Appendix). Without losing generality, we perform comprehensive double slit experiments with cross-double slit (Figure 26).

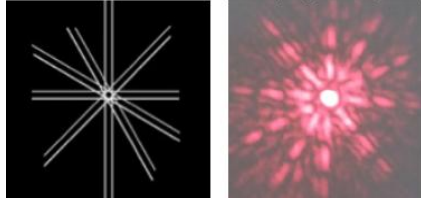


Figure 26. Cross double slit

This cross double slit consists of five double slits crossing at the same spot. Each of double slit creates an interference pattern independently.

Experiment-9: Testing Postulate-2 with cross-double slit
Experimental Setup-1 (Figure 27): shield-1 and shield-2 contact the detector and form a narrow channel.

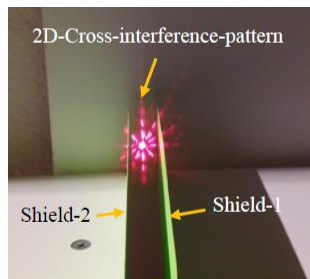


Figure 27. 2D-pattern vs. Channel (1)

Observation: the channel of two shields does not disturb the 2D-interference pattern.

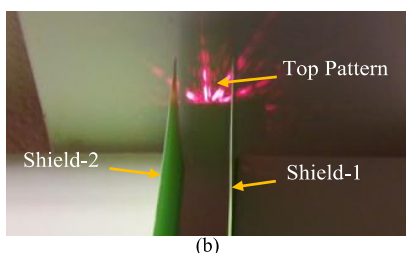
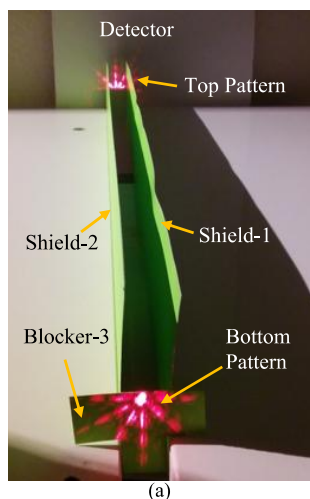


Figure 28. Testing Postulate-2 with Cross-double slit (2)

Experimental setup-2 (Figure 28a): using blocker-3 to block the bottom portion of the 2D-interference pattern.

Observation (Figure 28): the top portion of the 2D interference pattern is shown on the detector (Figure 28b), while the bottom portion is shown on blocker-3. Namely, 2D patterns are created independently and partially. Only particle can have such behavior.

Postulate-2 is consistent with experiments: in zone-3, photons move along predetermined trajectories that are straight lines to form fringes and thus, behave as particles.

Experimental setup-3 (Figure 29a): using blocker-3 to block bottom-right corner of the 2D-interference pattern.

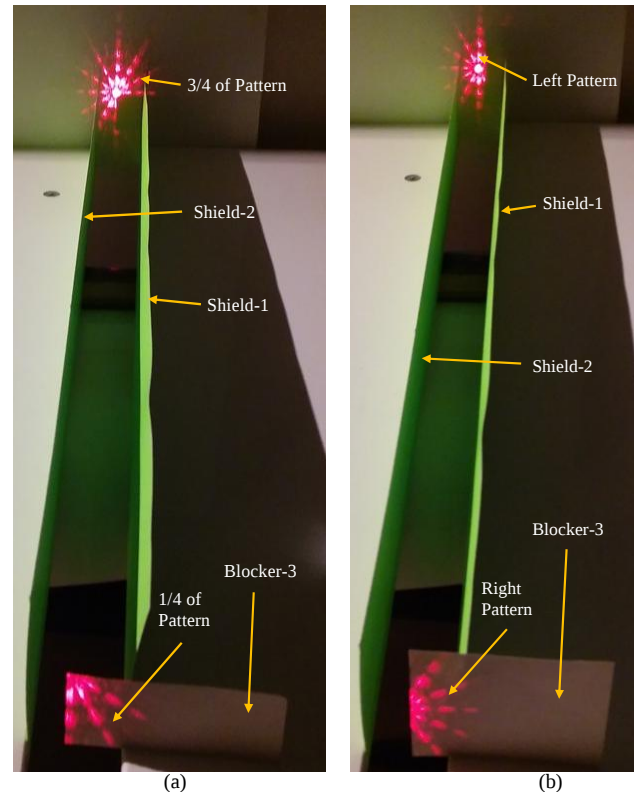


Figure 29. Testing Postulate-2 with Cross-double slit (3)

Observation (Figure 29a): the $\frac{3}{4}$ portion of the 2D interference pattern shown on the detector, while the bottom-right portion of the interference pattern shows on blocker-3.

Experimental setup-4 (Figure 29b): using blocker-3 to block right portion of the 2D-interference pattern.

Observation (Figure 29b): the left portion of the 2D interference pattern shows on the detector, while the right portion of the interference pattern shows on blocker-3.

Namely, 2D patterns are created independently and partially. Only particle can behave in such way.

Postulate-2 is confirmed experimentally.

3.3.5. Testing Range of Virtual Box

Experiment-10: searching the range of the Virtual Box.

Experimental Setup (Figure 30a): Moving a shield towards the double slit and observing. In this article, the shield is stopped at a position one inch from the double slit.

Observation (Figure 30b): both the "interference" pattern and the projection of the shield show on the detector. The latter is wider than the projectors in Figure 8, Figure 10, Figure 12 and Figure 13. The particle nature still shows.

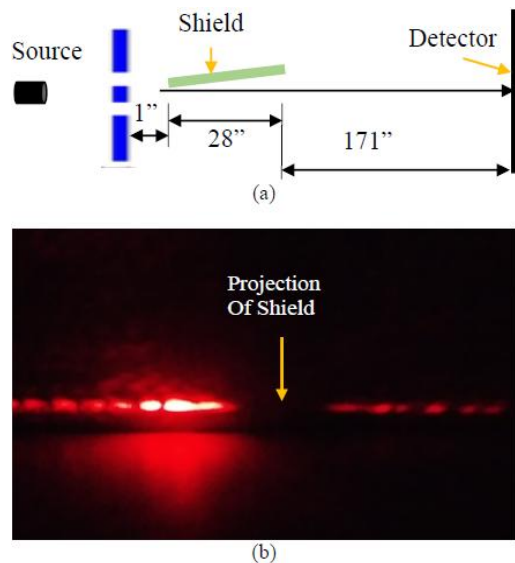


Figure 30. Schematic Setup and Observation

Thus, the width of zone-3 is at least 199 inches, in which photons behave as particles. Note that the distance between the slide and the detector is 200 inches.

Now let's calculate the width of the projection of the shield on the detector. The regular equation holds,

$$y = \frac{\lambda L}{d} m \quad (1)$$

For our experiment, the wavelength is 650 nm, the distance from the double slit to one end of the shield is one inch, the spacing between two slits is 0.25mm, and the cross-section, thickness, of the shield is 0.3 mm. Substituting into Eq. (1), we obtain $m \approx 4.6$, namely up to the 4th bright fringes are all blocked by the cross section of the shield.

4. Discussion

On the one hand, in the double slit experiments, it is interpreted that the light behaves as wave and creates an interference pattern on a detector/screen, which would not be expected if light behaves as particle. Indeed, the interference patterns do exist in the comprehensive double slit experiments.

On the other hand, we have experimentally shown novel phenomena that, in zone-3 of the double slit/cross-double slit apparatuses, photons indeed behave as particles, which would not be expected if photons behave as waves.

This phenomenon shows wave-particle coexistence, which violate complementarity principle and thus, seems a paradox, referred as wave-particle paradox.

We suggest an interpretation below to address this paradox.

A laser source emits photons as a beam of particles (as shown experimentally when testing postulate-1). Those photons travel into the virtual box. In the language of "wave", the function of the "virtual box" is a process of "forming" the distribution of photons as waves inside the "virtual box". In the language of "particle", the function of the "virtual box" is a process of "grouping" photons into different groups/streams that correspond to different

fringes respectively. Photons landing on the same fringe are defined as "in the same group". In practice, a "group" of photons propagates as a stream of particles and arrives at the same fringe continuously. The different groups/streams corresponding to different fringes are formed inside the virtual box. "Within, and only within, the "virtual box" the standard wave interference patterns are formed (Dr Ian Miller)".

Where the process completed, either in "wave language" or in "particle language", is defined as the right-boundary of the virtual box. When coming out of the "virtual box", photons behave as groups/streams of particles (as experimentally shown when testing postulate-2), and follow the straight-line trajectories that lead to the different fringes. Although the trajectory of each photon cannot be determined, the trajectory of each group/stream of photons is determined while they are inside the "virtual box". The trajectories of each group/stream of photons are shown by the evolution of each fringe after photons coming out the "virtual box". However, the trajectories cannot be directly observed at the right-boundary of the "Virtual box", because existing observation equipment can only register photons, but cannot detect the directions of each group/stream of photons simultaneously. The right-boundary is a point at which, different groups/streams of photons separate. One can observe the patterns/fringes only when different groups/streams of photons are separated. The mystery of double slit experiments is narrowed to the mystery of the mechanism of "forming" or "grouping" in Z-2.

Based on comprehensive double slit experiments, we suggest that (1) the "particle nature" of photons is intrinsic, the wave "nature" is secondary; and (2) restudy the mystery of double slit experiments, complementarity principle and wave-particle duality.

5. Conclusion

We propose and perform comprehensive-double slit/cross-double slit experiments with simple apparatuses to study the basic mystery of quantum mechanics. Novel phenomena are shown and are naked-eye-visible.

A significantly important fact is that all observations of experiments are consistent.

Based on three facts shown from above experiments, (1) shields have no "wave shielding effect" on fringes, i.e., photons do not behave as waves in Z-3; (2) each fringe is formed independently; (3) each fringe can be formed partially, we conclude that, in zone-3, i.e., before landing on the detector/screen, photons move along predetermined trajectories that are formed while photons were in the "virtual box", to form fringes and thus, behave as particles. Postulate-2 is confirmed experimentally.

We also show that, before arriving at a slide of double slit/cross-double slit, i.e., in Z-1, photons behave as particles. Postulate-1 is confirmed experimentally.

Now, we have more systematic and comprehensive experimental data, which make the mystery clearer and suggest a criterion that an interpretation of the double slit experiments should be able to explain all of those comprehensive-double slit experiments consistently.

Acknowledgements

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Appendix

A1. Cross-double Slit

Let us review cross-double slit apparatuses that can be used in comprehensive double slit experiments.

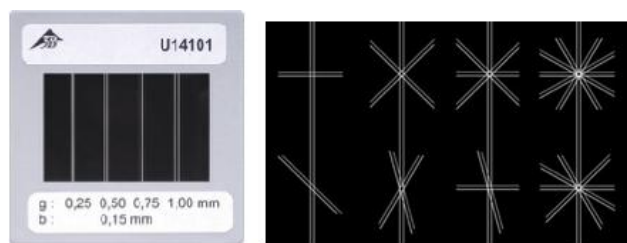


Figure A1. Double slit vs. Cross-Double slit

Figure A1 compares a slide of standard double slit with a slide of cross-double slit [25,26].

Next, let's show a standard double slit/interference pattern and some of cross-double slit/interference patterns without detail discussion.

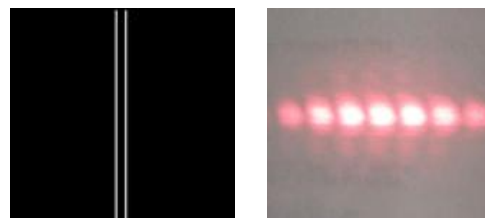


Figure A2. One double slit and interference pattern



Figure A3. Two crossing double slits and interference pattern



Figure A4. Two crossing double slits and interference pattern

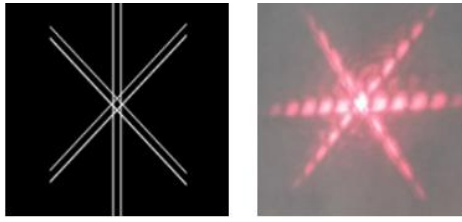


Figure A5. Three crossing double slits and interference pattern

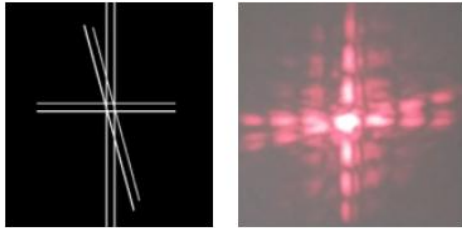


Figure A6. Three crossing double slits and interference pattern

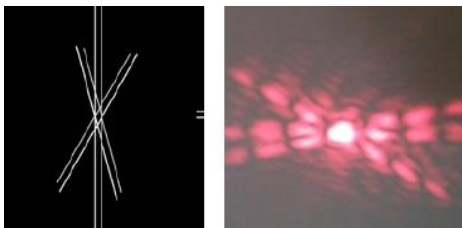


Figure A7. Three crossing double slits and interference pattern

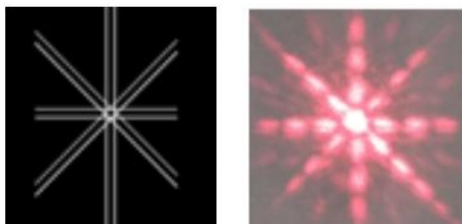


Figure A8. Four crossing double slits and interference pattern

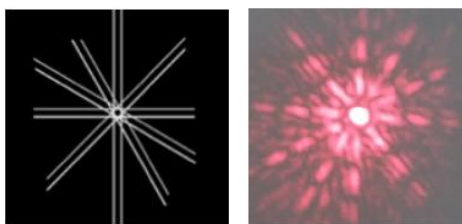


Figure A9. Five crossing double slits and interference pattern

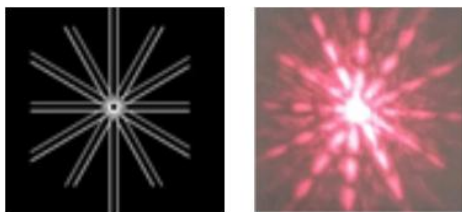


Figure A10. Six crossing double slits and interference pattern

There are many more varieties of cross-double slit apparatuses, either with different numbers of double slits

crossing together, or crossing at different angles, etc. Mathematically interpreting observations consistently is a challenge. The cross-double slit experiments are more mysterious than the standard double slit experiments.

A2. Which Way Cross-Double Slit Experiments

Which-Way 1D-double slit experiments support Bohr's complementarity principle, i.e., either wave (Figure A2) or particle (Figure A11).



Figure A11. Standard Double Slit Which Way Experiment

The following are the Which-Way 2D-cross-double slit experiments [27,28], which challenge Bohr's complementarity principle, i.e., both particle behavior (passing through double slit AB with an "observer" behind slit A) and wave distribution (passing through other double slits) coexist (Figure A12, Figure A13 and Figure A14). In the figures below, dashed slits indicate that an "observer" is behind that slit, or equivalently, that slit is covered.

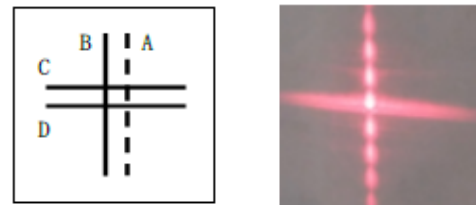


Figure A12. Observation at slit-A

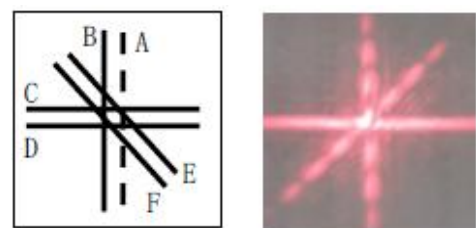


Figure A13. Observation at slit-A

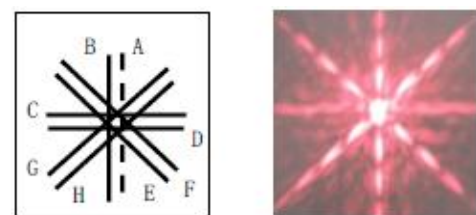


Figure A14. Observation at slit-A

